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Review Article

Additive Manufacturing: A Novel Method for Developing an Acoustic Panel Made of Natural Fiber-Reinforced Composites with Enhanced Mechanical and Acoustical Properties

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Natural fibers and their composites are being widely used in almost all the applications in this modern era. However, the properties of natural fibers have to be enhanced in order to compete with synthetic fibers. This review paper opens up additive manufacturing, as a novel method for developing an acoustic panel using natural fiber composites with enhanced mechanical and acoustical properties. This approach will help to replace synthetic-based acoustic absorbers with biodegradable composite panels in acoustic applications. This review also covers, poly(lactic acid) as a polymer matrix and its advantages, the available variety of natural fibers as reinforcement in terms of mechanical and acoustical properties. The natural fiber-based filaments used in additive manufacturing and acoustic panels made from the available natural fibers are also elaborated here. This review shows the importance of additive manufacturing and its application to develop novel acoustic panels made of agricultural waste.

1. Introduction

Additive manufacturing (AM), which is also known as 3D printing, is the process of combining materials to construct a three-dimensional object layer by layer. The input will be from the 3D model data which are drafted in designing software [1]. Additive manufacturing is used in many manufacturing divisions such as automotive, biomedical, and aerospace [2]. According to ISO/ASTM 52900, AM is classified into multistep process and single step process. The processes are categorized into binder jetting, directed energy deposition, material extrusion, material jetting, and powder bed fusion. Based on the materials used in the AM process, there are mainly three types of 3D printing methods available and they are liquid-, solid-, and powder-based AM. Stereo lithography (SL), fused deposition modeling (FDM), and polyjet are liquid-based AM. Laminated object manufacturing (LOM) is the solid-based AM. Powder bed and inkjet head 3D printing (3DP), prometal, laminated engineered net shaping (LENS), selective laser sintering (SLS), and electron beam melting are powder-based AM [3]. Out of all techniques, FDM is the most common technique used for printing fiber-reinforced polymer composites [4]. One of the main drawbacks of the FDM technique is that the printed composites will have slight void formation between the deposition lines [5]. This void formation in the additive manufacturing process can be turned as a favor for acoustical applications since acoustic absorption panels need a modest range of pores or voids to absorb the sound waves effectively [6]. In order to get the desired product with enhanced properties, filaments which are produced for the AM process has to be durable and resistant [7]. There are lots of materials that have been used in the additive manufacturing process. Some of the materials which have been in practices are pure polymers, polymer matrix composites, polymer ceramic composites, nanocomposites, and fiber-reinforced composites [2]. Recently, natural fiber-reinforced composite (NFRC) filaments seek attention in the field of AM as NFRC is economical and highly biodegradable and exhibits lower environmental impacts [8]. Malaysia is aiming for national target of 40% reduction in carbon emissions by 2020. Unfortunately, as per the carbon foot print report circulated by Roundtable on Sustainable Palm Oil (RSPO), it is found that net carbon emission in 2017 has increased by around 18% since 2014, from under 350,000 MT CO_2e to 420,000 MT CO_2e which has to be taken into an account [9]. The use of synthetic fibers will have environmental impacts like increased carbon footprint level during its entire life span [10], whereas bio-based polymers like PLA show lesser environmental impacts and proved to be an alternative for petroleum-based polymers [11].

2. Acoustic Panels Made of Natural Fibers and Their Evolution

Noise which originates from industries and residences is more bothering as they cause sleeping disturbances, headache, annoyance, and stress among the people. Hence, these noises have to be addressed immediately [12]. Acoustic panels can be used in controlling the sound by absorbing it and converting it into heat energy. Generally, acoustic panels will be containing porous synthetic materials like polyester, rock wool, and glass wool. Recently, acoustic panels made of natural fibers are becoming a trend. This is because most of the natural fibers are proven to be good acoustic absorbers and cost-effective [13]. Perforated panels are the one that support the usage of natural fibers in it. Usually, conventional perforated panels will be having holes with a larger diameter which could not provide satisfactory acoustic absorption. This problem leads to the discovery of microperforated panels which has a smaller diameter of pores in it [14]. In an acoustic panel made of natural fibers, its acoustic absorption is influenced by some of the factors like the fiber morphology, content of fiber, position of perforated plates, treatment of fiber, and so forth. In order to study about the position of perforation plates, Hosseini et al. placed perforation plates before and after the fiber layers and concluded that placing of perforation plates both before and after the fiber layers was eligible to increase acoustic absorption [15]. Bansod et al. placed the circular perforated plate made of mild steel plates in a circular pattern at both sides of fiber layers and observed that if the perforation plates are kept behind, there is an improvement in acoustic absorption in the high-frequency spectrum [16]. To know about the effect of fiber content on the acoustic absorption coefficient, Daniel et al. mixed the kenaf fibers in different ratios with PLA and hot pressed into a microperforated plate. They found that the composite with 30% of percentage of kenaf fibers has shown the maximum absorption coefficient [14]. Ismail et al. bonded the rice husk and sugarcane bagasse at different fiber contents using phenol formaldehyde resin which is later hot pressed into an acoustic panel. They determined that voids in rice husk encouraged acoustic absorption, whereas sugarcane bagasse offered sturdiness to the panel [17]. To study the effect of alkaline treatment on the acoustic absorption, Sari et al. molded the corn husk fibers which are treated with different ratios of sodium hydroxide into an acoustic panel. They found the fibers which are treated with 2% and 5% of NaOH exhibit a higher absorption coefficient [18]. In order to investigate about densities and thickness of fiber layers, Rachman et al. mixed the coir fibers at different densities with acetic acid as an adhesive at different percentage and hot pressed into an acoustic panel. Acoustic absorption coefficient was calculated. It has been found that sample with the higher density and lower percentage of acetic acid provides the highest acoustic absorption coefficient [19]. Berardi et al. made an acoustic panel by molding the fibers from coir, kenaf, wood, and hemp at different thickness of layers and concluded that acoustic absorption can be increased by increasing the thickness of the layers [13]. Liu et al. 3D-printed the perforated panel using polymer materials called VisiJet-SL (Clear) backed with recycled cotton fibers and revealed that the acoustic absorption coefficient can be varied by varying the perforation ratio [6]. Table 1 shows some of the acoustic panels made of natural fibers and their composites along with its methodology and key findings.

Apart from the abovementioned acoustic panels, these are also some of the acoustic panels made of natural fibers. Kang and Brocklesby produced a transparent microperforated plate in the acoustic window system and realized this system can be used for solar application [20]. Iannace et al. produced an acoustic panel by stuffing giant reeds in jute bags and conducted a case study to use the produced panel for classrooms [21]. Kaamin et al. stuffed kapok fiber in an egg tray and developed an acoustic panel which showed promising acoustical properties [22]. Chou et al. developed an interior adjustable acoustic panel which is suitable for adjusting the reverberation time without fixing up the whole room [23]. Acoustic insulation boards were developed using materials like sheep wool and green composites in different compositions, and they concluded these sound boards can be used for light weight applications [24]. These are some of the ways by which acoustic panels are made from natural fibers, whereas 3D printing of an acoustic panel made of natural fiber-reinforced composite is still to get recognized.

3. Recent Trends in Additive Manufacturing of NFRCs

At first, synthetic fibers made their way into the field of additive manufacturing. A review report by Goh et al. concluded that mechanical properties of the 3D printed composites are increased when reinforcements are added into the pure polymers. This report mainly dealt with synthetic fibers [25]. Some of the results based on the reinforcement of synthetic fibers are summarized as follows: Zhong et al. reinforced glass fibers with ABS as a matrix using FDM technology and found that the ABS-glass fiber composite exhibits better strength than pure polymer [26]. Tekinalp et al. reinforced carbon fibers with ABS and observed that increase in fiber content shows increased modulus and tensile strength which is greater than the conventional compression molding [5]. Table 2 shows some of the synthetic fibers that have been used in the FDM process and their enhancements.

Table 1: Acoustic panels made of natural fibers and their composites along with the methodology and key findings.

Materials used	Methodology	Factors investigated considering acoustic absorption	Key findings	References
Coir fiber	Perforated plates backed by coir fibers	Position of perforation plate and air gap	Acoustic absorption was improved especially in low frequency spectrum	[15]
Jute felts	Perforated plates backed by jute felts	Position of perforation plate and thickness of backed fiber	Usage of perforation plates helped in improving the acoustic absorption in low frequency spectrum without increasing the jute belt's thickness	[16]
Kenaf fiber	Hot pressing of the perforated plate	Fiber content	The highest acoustic absorption coefficient was recorded as 0.987 at 1521.02 Hz	[14]
Rice husks and sugarcane bagasse	Hot pressing of the perforated plate	Fiber content	The highest acoustic absorption coefficient was recorded as 0.58 at 4000 Hz	[17]
Coir	Hot pressing of the fiber	Density of the fiber layer	Acoustic absorption coefficient was observed to be 0.9 at 4000 Hz	[19]
Corn husk fiber	Molding of fibers	Alkaline treatment of fibers	Acoustic absorption coefficient was 100% in the frequency range between 1600 and 3250 Hz	[18]
Kenaf fiber, wood fiber, hemp fiber, and coconut fiber	Molding of fibers	Thickness of the fiber layer	All the natural fibers exhibited satisfactory acoustic absorption coefficient in midfrequency and high frequency spectrums	[13]
Recycled cotton fiber	3D printed perforated plate made of VisiJet-SL (clear) backed by recycled cotton fibers	Perforation ratio	Significant improvement of acoustic absorption especially in low to midfrequency spectrum	[6]
Natural fiber composites	3D printing of an acoustic panel	—	—	This review

Table 2: Synthetic fiber reinforcement in polymer and their enhancement [4].

Composite	Enhancement in properties
Short glass fiber-ABS	Tensile strength of the composite increases by 135%. The maximum tensile strength is found at 18% fiber content.
Short carbon fiber-ABS	Tensile strength of the composite increases by 114%. The maximum tensile strength is obtained at 40% fiber content.
Continuous carbon fiber-nylon	Tensile strength of the composite increases by 465%. The maximum tensile strength is peaked at 34% fiber content.
Continuous carbon fiber-PLA	Tensile strength of the composite increases by 332%. The maximum tensile strength is obtained at 6.6 wt.%.

According to Table 2, synthetic fiber reinforcement in the polymer matrix by the FDM process has shown a greater increase in mechanical property of the composites. Considering cost and environmental impact, reinforcement using natural fibers evolved [27]. Only limited research studies have been done in 3D printing of the natural fiber-reinforced composite received from fruits and plants. Stoof and Pickering initiated an experiment to 3D print the natural fiber-reinforced composite. They have successfully 3D printed the composite by reinforcing harakeke fiber and hemp fiber with PLA as a polymer matrix and made few conclusions as follows: 10% fiber content of hemp shows increased tensile than the polymer matrix and the tensile strength tends to decrease with an increase in the fiber content, whereas in case of harakeke fibers, tensile strength was noted to be decreased for 10% fiber content initially. Then, the tensile strength tends to increase for 20% fiber content [28]. Recent review article by Mazzanti et al. covered the research studies made on the 3D printed natural fiber composites and the factors influencing its mechanical properties and concluded that the addition of natural fibers as reinforcement increases the mechanical properties in few cases. They also added that the increase in percentage of natural fibers to the PLA decreases the strength of the composite, whereas the stiffness of the composite remains the same. Impact strength and elongation at break decreases with addition of natural fibers. On an overall basis, it can be seen that the mechanical properties of the 3D printed natural fiber composites has not increased drastically when compared to pure polymers. However, the mechanical properties of the 3D printed composites can be further enhanced by optimizing some of the process parameters (nozzle diameter, filament diameter, printing speed, melting temperature, infill geometry, infill thickness, number of layers, and thickness of layers), product parameters (fiber geometry and fiber morphology), and environmental conditions (humidity). From all the research and review made on 3D printed natural fiber composites, it can be commonly seen that the surface of the 3D printed composite contains gap, cracks, and pores. This pore, crack, and gap formation is considered as limitation in many of the research and review related to 3D printing of the fiber-reinforced composites [29]. The same characteristics was observed even in the 3D printed synthetic fiber composites [30]. Table 3 shows some of the research studies on 3D printing of the natural fillers along with discussion.

This void formation in the 3D printing process can be turned as an advantage in acoustical applications since surface of the acoustic absorbing devices needs perforation for its effective acoustical absorption [6]. As of present, physical properties, mechanical properties, rheological properties, and some other characteristics like water absorption, warping, and phase morphology of the 3D printed NFRC were investigated by the researchers, whereas this review provides platform for the researchers to develop an acoustic panel made of NFRC by additive manufacturing and to investigate its acoustical properties.

4. Additive Manufacturing of Polymers

Additive manufacturing started its journey with the use of pure polymers. Polymers are made up of many numbers of small molecules called monomers. Monomers combine to form polymers by the process called polymerization. Polymers are classified based on their occurrence, thermal response, physical properties, and mode of formation and also based on online structures [45], which are shown in Figure 1. There are many polymers like polyester, polypropylene (PP), polyurethane (PU), polyethylene (PE), polystyrene, and polycarbonate that can be used as the matrix in the composite which will be covered under the above classifications. However, only few polymers make their way into the additive manufacturing process because the working temperature of FDM is around 300°C which makes only some of the thermoplastic polymers and other polymers to find their way in to the additive manufacturing process [2]. Thermoplastic polymers are those that can be molded above the threshold temperature and returns to the solid state upon cooling [46]. Some of the examples for thermoplastic polymers are acrylonitrile buta-styrene (ABS), polyethylene, polypropylene, polystyrene, polyvinyl chloride, nylon, acrylic, and Teflon. Moreover, the other main reasons are that thermoplastic polymers are not detached during the entire 3D printing process, whereas the other types of polymers are not suited [47]. There are two sources of polymers which can be used in 3D printing filaments. First, they are from recycled plastics. Example: poly(lactic acid) and acrylonitrile butadiene styrene. Secondary, they are from bioplastics. Example: PLA and polyhydroxyalkonates (PHA). Table 4 shows the list of commonly used polymers used as filaments in FDM technology.

The petroleum-based polymers get out of selection as they increase the carbon footprint value of the product [49]. PHA and PLA are the only bio-based polymers, where the production cost of PHA is higher [50] and the production cost of PLA is very lower [51]. Ivey et al. experimented on extrusion additive manufacturing with carbon fiber-reinforced PLA filaments, and he found that PLA holds good for the extrusion additive manufacturing process for the fiber content of 15%. Mechanical properties of the fiber-reinforced filament were observed to be higher than pure PLA filaments [52]. Rodriquez et al. produces specimens using ABS and PLA by FDM additive manufacturing and found specimens made using PLA exhibits good rigidity, increased tensile strength, and strong bonds between layers of PLA and concluded that PLA is most suitable for the additive manufacturing process [53].

PLA is synthesized from raw materials like rice, corn, and sugar beets and is considered as one of the thermoplastic aliphatic polyesters. PLA has good renewability and compatibility compared to the other biodegradable polymer materials [54]. PLA as a polymer matrix has one of the unique characteristics of being nontoxic [55]. PLA as a polymer matrix with natural fibers as a reinforcement proved out to be most economical and efficient system that can be used widely for many applications [56]. PLA is a one of the best eco-friendly polymers which shows a higher rate of degradation when it is filled in lands and requires lesser energy for production. Global warming caused by bioplastics is negligible compared to conventional plastics [57]. PLA as material itself shows zero carbon footprint, but during the process of PLA, its carbon emission is comparatively little higher than other polymers. But as a whole, carbon footprint of PLA is less compared to all polymers [49]. PLA filaments which are used can be recycled and reused with the certain amount of strength are left behind [58]. Table 5 shows the properties of PLA.

However, there are certain drawbacks that have been registered to the usage of pure polymers like PLA mainly the innate brittleness and low impact strength

Table 3: Some of the research studies on 3D printing of the natural filler composites and its discussion.

Polymer	Natural fillers	Discussion	Void (pore, crack, or gap) formation	Reference
PLA	Hemp and harakeke	3D printing of the natural fibers has been initiated	Yes	[28]
PLA	Bamboo and flax	The length over diameter ratio of the fibers has been investigated	Yes	[31]
PLA	Wood	Effect of printing layer thickness on the water absorption and mechanical properties is investigated	Yes	[32]
PLA	Wood	Physical and mechanical properties of the filaments were studied varying the wood content	Yes	[33]
PLA	Aspen wood flour	Adding 5% wood content to the polymer does not change the melting temperature of the composite	Yes	[34]
PLA	Pine lignin	Phase morphology and the mechanical properties of the printed material were studied	Yes	[35]
PLA	Thermomechanical pulp (TMP)	Water absorption and mechanical properties of the composite were investigated	Yes	[36]
PLA	Sugarcane	Effect of printing orientation on mechanical properties of the composite was studied	Yes	[37]
PHB	Sawmill	Warping of the composite with respect to addition of fillers was investigated	Yes	[38]
Polyethylene	Thermomechanical pulp	Polyethylene-based filament for AM has been initiated	Yes	[39]
ABS	Rice straw	Water absorption and mechanical properties of the composite were studied	Yes	[40]
ABS	Macadamia nutshells	Mechanical properties of the composite were studied	Yes	[41]
Polypropylene	Hemp and harakeke	This study was conducted to check the potentiality of natural fiber-reinforced polypropylene filaments	Yes	[42]
bioPE	TMP	Mechanical properties of the composite were studied	Yes	[43]
Polyurethane	Wood flour	Rheological and mechanical properties of the composite were discussed	Yes	[44]

of the PLA [60]. Fibers are reinforced with polymers to overcome the above issue and can be used for many applications mainly for its high strength, cost reduction, and lighter weight [61].

5. Natural Fibers as Reinforcement

There are mainly two types of fibers used as reinforcements in the composite, namely, synthetic fibers such as glass fibers, aramid fibers, carbon fibers, quartz, boron, ceramic fibers, and natural fibers. Natural fibers are obtained from animals, minerals, and plants. Natural fibers are one of the highly used reinforcements in the composites as they are capable of producing higher specific strength and stiffness than other materials [62]. Plant natural fibers which have cellulose as one of its main constituents are broadly classified into 7 categories, and they are bast natural fiber, leaf natural fiber, fruit natural fiber, seed natural fiber, wood natural fiber, stalk natural fiber, and grass natural fiber [63]. The classification and subclassification of natural fibers are shown in Figure 2. Plant-based natural fibers are produced by two types of plants, and they are primary plants and secondary plants. Primary plants get their names because they are primarily grown for producing fibers. Some of the examples of primary plants are sisal, cotton, kenaf, and hemp. In the case of secondary plants, fibers are obtained from the plants as a by-product. Some of the examples of secondary plants are oil palm, coconut coir, banana, and pineapple [64]. Out of all the available fibers that can be used as reinforcements, natural fibers are one of the most suitable materials which can be used in the production of biodegradable and light-weighted composites. These composites are being used in the field of automobiles, electrical, railways, and storage devices [65]. Natural fibers are available in abundant and are biodegradable [66]. Table 6 shows the availability of natural fiber across the world.

Synthetic fibers like glass, carbon, and aramids exhibit better mechanical properties compared to natural fibers. Table 7 provides the mechanical properties of the natural and synthetic fibers comparatively.

Even though synthetic fibers possess higher mechanical properties than natural fibers, natural fibers are being renewable and are eco-friendly [68]. On the overall basis,

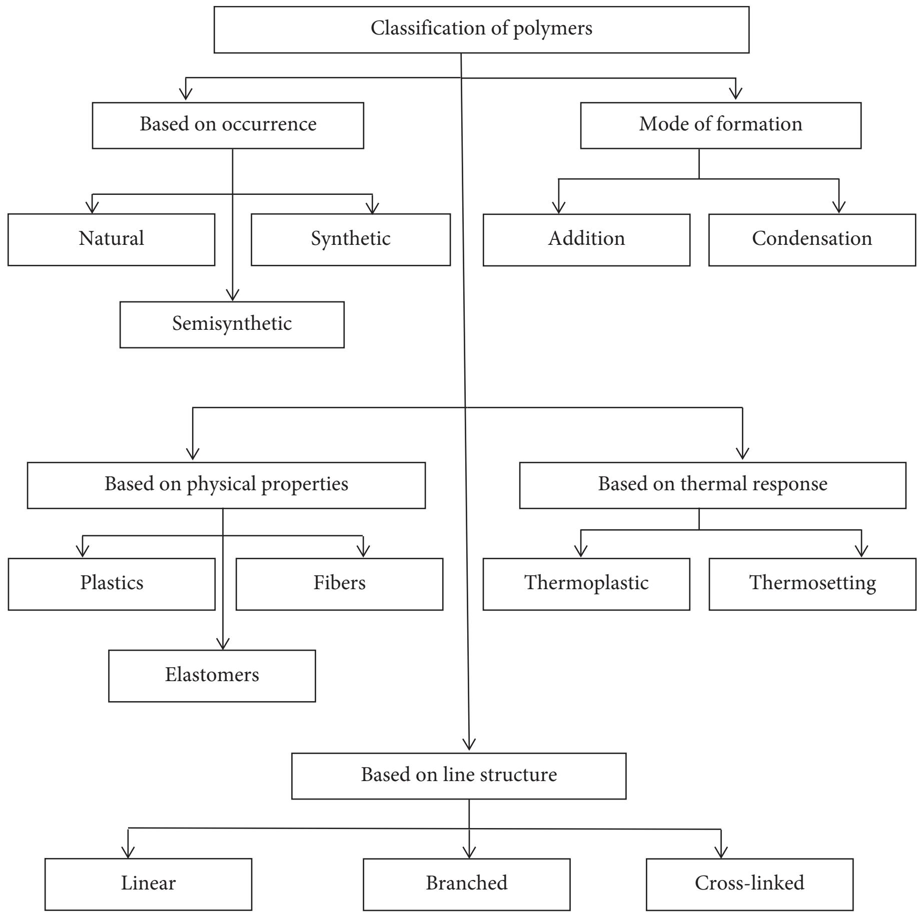

Figure 1: Classification of polymers [45].

Table 4: List of commonly used polymers as filaments in FDM [48].

Polymers	Source	Advantages
ABS	Petroleum	Cheap and light weight
PET	Petroleum	Recyclable and odorless
PLA	Starch, sugar cane	Bio plastic, biodegradable, nontoxic, and odorless
PVA	Petroleum	Nontoxic and biodegradable
PA	Synthetic fibers	Light weight and water resistance
PHA	Sugar	U-V stable

Table 5: Properties of PLA [59].

Properties	INGEO 2003D	ASTM standard
Tensile strength (MPa)	52	D882
Tensile modulus (GPa)	3.4	D882
Tensile yield strength (MPa)	61	D882
Specific gravity	1.21	D792

natural fibers exhibit many of the positives like they can produce less weighted composites; they are biodegradable, available in abundant and are economical [65]. This makes them to be suitable material in the part of composites as reinforcement. Table 8 shows the price comparison between natural fibers and synthetic fibers.

Regarding the acoustical properties, natural fibers like kapok exhibit better acoustical absorption than glass wool [69]. Comparison of acoustic absorption coefficient of natural fibers and synthetic fibers is shown in Table 9. Table 10 shows the mechanical properties of all available natural fibers.

It can be seen that natural fibers like hemp, kenaf, and coconut exhibit better acoustic absorption than synthetic fibers.

Natural fibers from banana, bamboo, jute [81], kapok [82], milkweed [83], softwood [84], hardwood [85], rice husk, sugarcane [17], wheat straw [86], and corn husk [87] exhibit good acoustical properties and are used for applications like sound boards, automobiles, and thermal and acoustic panels. Acoustic absorption coefficient (acoustical property) values of the available natural fibers are listed in Table 11.

Hence, from Table 11, it can be concluded that natural fibers can be used as reinforcements in composites which will be used for acoustical applications.

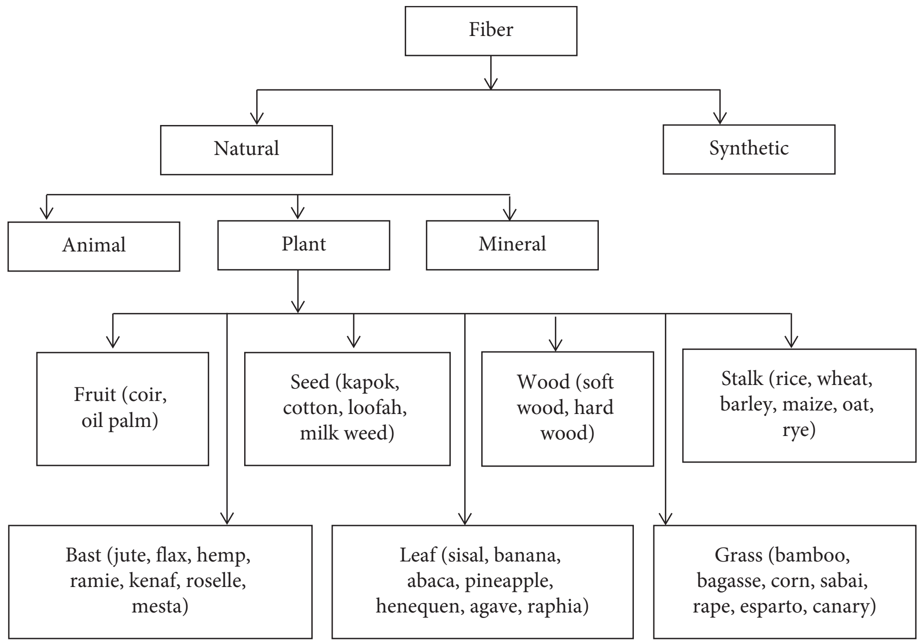

Figure 2: Classification and subclassification of natural fibers [63].

Table 6: Availability of natural fibers [66].

Fiber	Source	World production (10^3 tons)
Coir	Stem	100
Oil palm	Fruit	Abundant
Flax	Stem	800
Kenaf	Stem	760
Jute	Stem	2,600
Ramie	Stem	110
Hemp	Stem	210
Roselle	Stem	250
Sisal	Stem	370
Banana	Fruit	210
Abaca	Stem	70
Pineapple	Leaf	Abundant
Cotton	Stem	18,550
Wood	Stem	1,755,020
Rice	Stem	Abundant
Wheat	Stem	Abundant
Bamboo	Stem	10,000
Bagasse	Stem	75,000

Table 7: Mechanical properties of natural and synthetic fibers comparatively [67].

Fibers	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)
Carbon	1.4	4000	23.0–40.0
Aramid	1.4	3000–3200	63.0–66.0
S-Glass	2.5	4500	85
Coir	1.2	150–250	3.0–6.0
Jute	1.4	390–750	12–32
Hemp	1.45	500–1000	65

Reinforcing synthetic fibers with PLA as a polymer matrix in the composite has drastically increased the mechanical properties of the composite [92]. Considering the cost and environmental impacts, reinforcing natural fibers with various polymer matrices such as polypropylene, polyester, epoxy matrix, and polyethylene is becoming a trend [67]. In Malaysia, natural fibers like coconut coir, coconut husk, oil palm, and paddy are available in

Table 8: Comparison of price between natural and synthetic fibers [8].

Fibers	Cost in US$/ton
Coir	350
Abaca	340
Kenaf	400
Glass fiber	1,250–1,750
Carbon fiber	12,000

Table 9: Comparison of acoustic absorption coefficients between natural and synthetic fibers [70].

Fibers	Thickness (mm)	Absorption coefficient			
		250 Hz	500 Hz	1000 Hz	2000 Hz
Rock wool	50	0.29	0.52	0.83	0.91
Glass wool	50	0.45	0.65	0.75	0.80
Polyurethane	50	0.30	0.68	0.89	0.79
Polystyrene	50	0.22	0.42	0.78	0.65
Kenaf	50	0.48	0.74	0.91	0.86
Hemp	40	0.59	0.60	0.56	0.52
Coconut	35	0.28	0.40	0.64	0.74

Table 10: Mechanical properties of natural fibers.

Fibers	Type	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	References
Coir	Fruit	1.2	150–200	3.0–6.0	[62]
Oil palm	Fruit	0.7–1.5	250	3.1	[62]
Flax	Bast	1.35	350–1050	28	[62]
Kenaf	Bast	1.2	290–950	50	[62]
Jute	Bast	1.23	180–775	12–28	[62]
Ramie	Bast	1.44	400–950	60–120	[62]
Hemp	Bast	1.35	550–1100	65–75	[62]
Roselle	Bast	0.75–0.8	300–850	25–60	[71]
Sisal	Leaf	1.2	500–800	9.0–23	[62]
Banana	Leaf	1.35	520–920	8–35	[62]
Abaca	Leaf	1.5	12	41	[72]
Pineapple	Leaf	1.52	410–1625	34–85	[66]
Agave	Leaf	1.36	385	—	[73]
Raphia	Leaf	1.53	152–270	—	[74]
Kapok	Seed	0.38	90–95	4	[72]
Cotton	Seed	1.55	300–700	5–10	[72]
Loofah sponge	Seed	0.3–0.65	11.2	1.32	[75]
Milk weed	Seed	0.97	280–380	8.2–9.2	[76]
Soft wood	Wood	1.5	1050	40	[62]
Hard wood	Wood	1.2	1000	38	[62]
Rice	Stalk	1.65	450	1.2	[62]
Wheat	Stalk	1.6	275	4.5–6.5	[62]
Barley	Stalk	—	—	0.3–0.6	[77]
Maize	Stalk	—	12–100	1–20	[78]
Bamboo	Grass	0.8–1.4	390–1100	10–30	[62]
Bagasse	Grass	1.2	20–300	—	[62]
Corn	Grass	0.344	160–175	4.5–5.1	[18]
Sabai	Grass	—	76	—	[79]
Esparto	Grass	1.3–2.1	18–28 (cN/tex)	—	[80]

abundance. These natural fibers are mainly used for energy harvesting, and most of them are generally disposed in land, causing land problems [93]. Hence, it encourages many of the researchers to utilize these natural fibers as reinforcement in the composite rather than getting disposed. There are many natural fibers available, and each exhibits different properties. There is a differentiation in properties of fibers because of their differences in shape, length, density, and weight. Property of the natural fibers is also defined by the content of cellulose it contains [67]. Thus, selection of fiber is one of the important factors to be considered as it is responsible for the increase in tensile strength, impact strength, hardness, toughness, and also the acoustical property of the composite. Adding to that, selecting the

Table 11: Acoustical absorption coefficient of natural fibers.

Fibers	Fiber properties	Frequency (Hz)	Absorption coefficient (α)	References
Coir	Thickness, 35 mm	500	0.84	[70]
Oil palm	Thickness, 50 mm	1000	0.90	[88]
Flax	Diameter, 21.8 μm	500	0.40	[89]
Kenaf	Thickness, 50 mm	500	0.74	[70]
Jute	Diameter, 81.2 μm	500	0.20	[89]
Ramie	Thickness, 40 mm	800	0.60	[90]
Hemp	Thickness, 40 mm	500	0.60	[70]
Sisal	Diameter, 213 μm	500	0.10	[89]
Cotton	Diameter, 13.5 μm	500	0.50	[89]
Bagasse	Thickness, 20 mm	500	0.13	[91]
Corn	Thickness, 20 mm	500	0.16	[91]

physical properties like the fiber diameter, layer thickness, and bulk density for developing an acoustic panel has to be considered as these are responsible for effective absorption [94]. Prominent enhancement in the mechanical properties has been reported when reinforcements are done. Daniel et al. reinforced the kenaf fiber with PLA as a matrix and concluded that 30% fiber content shows the maximum sound absorption coefficient of 0.987 at a frequency of 1521 Hz and increase in mechanical properties as well [14]. All the available natural fibers reinforced with some of the polymer matrix and their resulting enhanced mechanical and acoustical properties are tabulated in Tables 12 and 13.

Some of the commercially available natural fiber-PLA-based reinforced filaments in the AM process are tabulated in Table 14, and some of the bio-based PLA filaments in AM which are in research stages are tabulated in Table 15. Figure 3 shows the overall list of materials used in FDM technology.

6. Methodology to Develop an Acoustic Panel Using Natural Fiber-Reinforced Composite

The methodology to develop an acoustic panel includes the following procedures: (i) compounding the polymer matrix with reinforcement. Melt blending and extrusion are the most common compounding techniques in this recent era; (ii) production of filament; and (iii) developing an acoustic panel by additive manufacturing. Figure 4 shows the novel method to develop an acoustic panel using natural fiber-reinforced composite.

6.1. Techniques for Compounding Polymer Matrix with Reinforcement

6.1.1. Melt Blending. There are many types of techniques available which are used for producing PLA polymer composites. Some of the techniques which are commonly used are injection molding, transfer molding, and compression molding [136]. These techniques use moldings as a main tool by which researchers can produce the polymer composites. There are also techniques which are used in compounding the reinforcement into the polymer matrix without the moldings. Out of all the available techniques, melt blending is one of the easier and environmental friendly techniques for producing polymer composites [137]. Ibrahim et al. experimented with kenaf fibers as reinforcement in PLA as a polymer matrix by the melt blending technique [138]. Hao et al. melt-blended PLA as a polymer matrix with sisal fibers as a reinforcement and epoxy as a binder and concluded that the composite exhibits improved interfacial bonding [139]. Composites with enhanced mechanical properties are produced by the melt blending technique [61]. There are mainly two types of mixers by which melt blending is performed, and they are internal mixers (e.g., Brabender mixer and Banbury mixer) and continuous mixer (e.g., Buss kneader) [140]. Haramen et al. melt-blended PLA as a polymer matrix with oil palm empty fruit bunch fiber using Brabender internal mixer, and the composite shows promising mechanical properties by adding plasticizer [141]. Daniel et al. melt-blended PLA as a polymer matrix with kenaf fibers using Brabender internal mixer, and the composite with different compositions is tested for both mechanical and acoustical properties [14]. The temperature for the process can be maintained between 180°C and 190°C considering the melting temperature of pure PLA [138]. The rotor speed of the mixer can be selected as 50 rpm as it exhibits high intensity of mixing and maximum shear rate [140].

6.1.2. Extrusion. Extrusion is defined as the process of imposing the material into the die under various conditions to achieve the required product [142]. Extrusion is widely used in many of the applications, and they are used in food industry, pharmaceutical industry, plastic industry, and rubber industry [143]. Extrusion, on allowing the researchers to define the parameters like rotating speed, residence time, and temperature, is being responsible for good dispersion of fibers and orientation of fibers, thereby influencing the properties of the composite [144]. Steuernagel reinforced natural fibers with polymer composites using the extrusion technique and concluded that there is a good dispersion of fibers in the matrix [145]. Gamon et al. compounded natural fibers from bamboo and miscanthus with PLA as a polymer matrix using the extrusion technique [146]. Also, extrusion is considered one of the most economical processes with a lesser processing time. Some of the advantages of extrusion techniques are as follows; extrudes show uniform content, and fine particles

Table 12: Natural fibers with various polymer matrices and their resulting enhancement in mechanical properties.

Fibers	Polymer matrix	Enhancement in properties	References
Coir	PLA	The impact strength of the matrix is increased by 28% at 3% fiber content.	[95]
Oil palm	PLA	The impact strength and tensile strength of the matrix are increased by 2% and 5%, respectively, at 30% fiber content.	[96]
Jute	PLA	The tensile strength and stiffness of the matrix are almost doubled at 40% fiber content.	[97]
Flax	PLA	There is an increase in tensile stress of the matrix by 5.6% at 30% fiber weight.	[98]
Hemp	PLA	There is an increase in 21.5% of tensile strength of the matrix at 40% fiber content.	[99]
Ramie	PLA	The 30% fiber content shows increase in mechanical properties than the matrix.	[100]
Kenaf	PLA	There is 85.4% increase in tensile strength of the matrix at 70% fiber weight.	[101]
Sisal	PLA	There is an increase in tensile strength of the composite by 34.7% at 30% short fiber weight than long fiber.	[102]
Banana	PLA	Tensile strength of the composite almost increases by 15.11% than that of matrix at 20% fiber content.	[103]
Abaca	PLA	There is an increase in tensile strength and impact strength by 14.8% and 58.4% at 30% fiber content.	[104]
Pineapple	PLA	Tensile strength of the composite almost doubles at 50% fiber weight than the pure PLA.	[105]
Agave	PLA	At 40% fiber content, impact strength of the composite increases by 71%.	[106]
Cotton	PLA	There is an increase in tensile strength and impact strength of the composite by 26.8% and 24.1%, respectively, at 40% fiber content.	[107]
Loofah	PLA	Tensile strength and impact strength of the composite increases by 16.5% and 19.6%, respectively, at 2% fiber weight.	[108]
Milk weed	PLA	Tensile strength of milkweed/PLA composite was found to be 48.1 MPa at 8% fiber content which is greater than the pure PLA.	[109]
Wood	PLA	Impact and tensile of the composite increases by nearly 7.8% and 0.36% at 20% and 40% wood flour content.	[110]
Rice	PLA	There is an increase in flexural modulus by 15% at 20% rice husk content.	[111]
Wheat	PLA	Tensile modulus of the composite increased at 30% wheat straw content. Maleated PLA was used as a compatibilizer to enhance the tensile and flexural strength.	[112]
Oat	PLA-PP	Improved storage modulus of the composite was recorded at 30% fiber content.	[113]
Rye	PLA	The tensile and impact strength of PLA-rye composite is almost doubled when compared with PP-rye composite.	[114]
Bamboo	PLA	Impact strength of the composite almost doubled when medium bamboo fibers are used at 40% fiber content.	[115]
Corn	PLA	There is an increase in tensile strength of the composite by almost 21.7% at 1% fiber content.	[116]
Sugarcane	PLA	Flexural and elastic modulus of the composite increases by 25.5% and 8.97% at 30% fiber content, respectively.	[117]
Mesta	PLA	There is a satisfied increase in tensile strength of the composite. Flexural strength of the composite was increased by 25% at 50% fiber content.	[118]

Table 12: Continued.

Fibers	Polymer matrix	Enhancement in properties	References
Esparto	PLA	Reinforcement at fiber content up to 40% fiber content shows superior mechanical and thermal properties.	[119]
Rape	TPS	Tensile strength of the composite increases by 95% when rapeseed fibers are reinforced.	[120]
Canary	Epoxy	Various adhesives and pretreatment method have been followed. Out of all, canary with epoxy provides better mechanical properties.	[121]
Roselle	RF	Tensile strength and flexural strength of the composite increases by 62% for short fibers at 1 : 1.5 ratio of resin.	[122]
Raphia	Polyester	At 20% fiber loading, microhardness of the composite increases by about 11.67% than the matrix.	[123]
Kapok	Polyester	In case of kapok hybrid composite, impact strength is increased by 65.2% at 50% kapok fabric and 50% glass.	[124]
Barley	PP	At 40% fiber content, barley composite shows improved tensile and impact strength than coconut and wood fiber.	[125]
Maize	PCL	Tensile strength of the composite almost increases by 78% at 66% fiber content.	[126]
Sabai	Sand	At 1% fiber content, sabai fiber composite shows good benefits.	[127]

Table 13: Natural fibers with various polymer matrices and their resulting enhancement in acoustical properties.

Fibers	Polymer matrix	Enhancement in properties	References
Kenaf	PLA	Acoustic absorption coefficient was recorded as 0.987 at the frequency of 1521.02 Hz for 30% fiber content.	[14]
Jute	PP	At 50% fiber content, the maximum acoustic absorption coefficient was 0.175 at the frequency of 1250.	[81]
Kapok	Polyester	Acoustic absorption coefficient was peaked to 0.83 at 2500 Hz for 90% fiber content.	[82]
Flax	Epoxy	Flax/epoxy composites show better acoustical absorption than glass/epoxy composites.	[128]
Banana	PP	Acoustic absorption coefficient was recorded as 0.13 at a frequency of 1250 Hz for 50% fiber content.	[81]
Bamboo	PP	For 50% fiber content, acoustic absorption coefficient was 0.2 at a frequency of 1250 Hz.	[81]
Tea leaf	PU	24% fiber content of tea fibers provides best acoustic absorption of 0.75 in midfrequency ranges.	[129]
Wood	Polyester	The peak acoustic absorption was 0.97 at a frequency of 4660 Hz at 3 : 1 fiber to matrix ratio.	[130]
Wood	PE	Maximum sound absorption was observed from 2000 Hz onwards.	[131]
Kenaf and rice straw	PP	Kenaf/PP composites show better acoustic absorption than rice/PP composites.	[132]
Kenaf, coir, ijuk, oil palm	Natural rubber	Acoustic absorption coefficient is peak for kenaf at 700 Hz–800 Hz, coir at 1000 Hz–1075 Hz, oil palm at 850 Hz–1200 Hz, and ijuk at 3200 Hz–3400 Hz.	[133]

Table 14: Commercially available PLA-based filaments [134].

Fibers/materials	Polymer	Company
Pine/wood fill	PLA	ColorFabb, NL
Bamboo/bamboo fill	PLA	ColorFabb, NL
Straw plastic/dried crop residues	PLA	Jinghe co., CN
Laywoo/cherrywood	PLA	CC products, DE

which are added as additives are uniformly distributed [143].

There are mainly three types of extruders available, and they are screw extruders, roller-type extruders, and piston extruders. Out of all the three types of extruders, screw extruders are one of the most commonly used extruders in recent times. Screw extruders are categorized as single screw

Table 15: Available bio-based polymer filaments.

Fibers/materials	Polymer	References
Dried distilled grains	PLA	[134]
Paulownia wood	PLA	[134]
Osage orange wood	PLA	[134]
Kraft lignin	PLA	[35]
Oil palm fiber	HDPE	[27]
Cotton	LDPE	[135]
Thermomechanical pulp	PE	[39]
Hemp	PLA	[28]
Harakeke	PLA	[28]

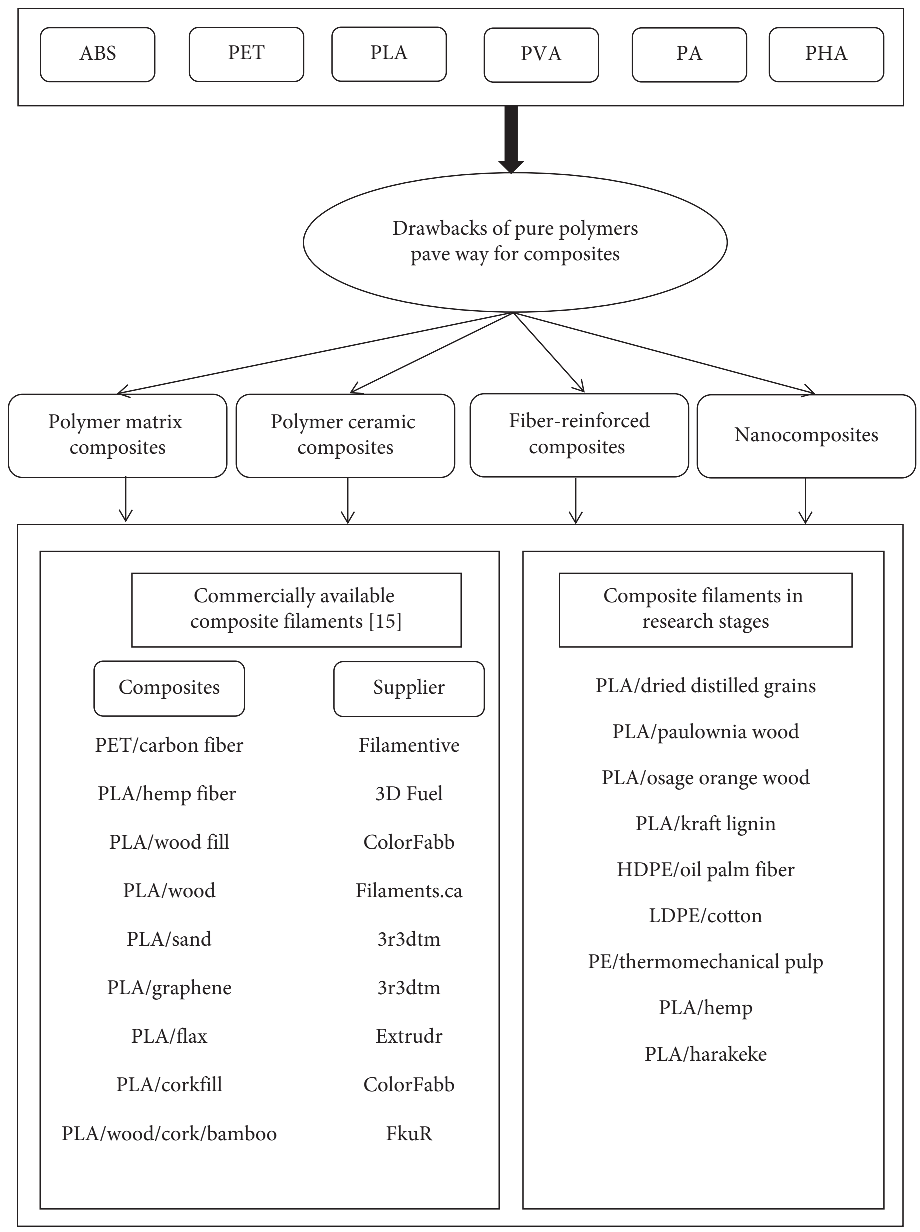

Figure 3: Overall list of materials used in FDM technology.

and twin screw extruder [142]. Table 16 shows the difference between single screw and twin screw extruder. The temperature of the extrusion process can be maintained at 180°C to 190°C considering the melting temperature of pure PLA [148].

6.2. Filaments for Additive Manufacturing. Filaments are produced by melting the polymers and extruding it to the spinneret to convert the melted polymer into solidified filaments. This process is called spinning. There are

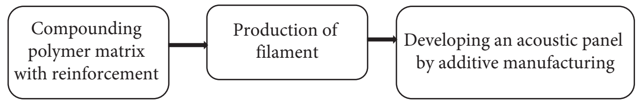

Figure 4: Novel method to develop an acoustic panel using natural fiber-reinforced composite.

Table 16: Difference between single screw and twin screw extruder [147].

Parameters	Single screw	Twin screw
Consumption of power (kJ/kg)	910 to 1520	410 to 620
Distribution of heat	Temperature difference is larger	Temperature difference is smaller
Rigidity	High	Low
Dissipation of power	Larger shear force	Smaller shear force
Cost	Low	High
Degasification	Simple	Complex
Water content (%)	12 to 35	10 to 96

mainly four types of techniques for producing filaments, and they are dry spinning, wet spinning, melt spinning, and gel spinning. Dry spinning and wet spinning are used when polymers need to be dissolved in solvents [149]. There are many natural fiber-reinforced polymer filaments available commercially, and also some are in research stages.

6.3. Additive Manufacturing Process. There will be problems like uneven finish during 3D printing of NFRC [28] which can be sorted out by optimizing its process and product parameters. Process parameters (nozzle diameter, filament diameter, printing speed, melting temperature, infill geometry, infill thickness, number of layers, and thickness of layers), product parameters (fiber geometry, fiber content, treatment of fiber, and fiber morphology), and environmental conditions like humidity of the fiber will be responsible for the mechanical and acoustical properties of the panel. Recent review article by Mazzanti et al. covered the product and process parameters that influences the mechanical properties of the 3D printed NFRC [29], whereas effect of product and process parameters on the acoustical properties of the 3D printed NFRC has to be investigated further. However, review article by Mamtaz et al. covered some of the properties like the fiber size, bulk density of the fiber, and sample layer thickness in order to obtain optimum acoustic absorption especially at lower frequency spectrums [150]. Parameters like porosity, tortuosity, flow resistivity, thermal characteristic length, and viscous characteristic length have to be optimized for effective sound absorption as these parameters influence acoustic absorption [151]. Moreover, perforation ratio should be considered as one of the important factors in designing an acoustic absorbing device for its effective absorption [152]. In general, natural fibers and NFRC experience few drawbacks such as they are vulnerable to microbial growth [153], have lower mechanical properties [134], and provides poor resistance to heat and flames [154]. These drawbacks are expected to be addressed when the NFRC are mixed with additives [155].

7. Carbon Footprint and Its Impact

Earlier, developing a product itself was made as one of the greatest achievements. But, in recent times, developing a product which has lesser environmental impacts is coming into business. Adding to that, carbon footprint of the product is one of the highly noted topics in this modern era. Carbon footprint value of the product has created a high background because it is directly impacting the climatic changes. Natural products and their biomass are providing good support to all countries in terms of economy. At the same time, the emissions of carbon into the atmosphere are also growing proportionally which is not a good sign. This increase in carbon footprint is having a negative impact on the climatic changes [156], thereby affecting the natural vegetation of the country. Carbon footprint of a product can be evaluated and optimized by life cycle assessment (LCA) [157]. LCA has two life cycles of the product: Business-to-Customer (B2C) and Business-to-Business (B2B). B2C estimates the emission of a product from raw material to disposal, whereas B2B estimates the emission till the development of product. Value of carbon footprint is negligible in biopolymers when compared to other polymers [11]. There are varieties of polymers used in producing biocomposite filaments for the additive manufacturing process. PLA as a polymer shows zero carbon footprint, whereas polymers like PE, PP, and PET show a higher carbon emission [49]. Moreover, processing of PLA also produces lesser carbon emissions as its processing stages involve lesser electricity and take energy from renewable sources [158]. Surprisingly, biopolymer composites show higher carbon footprint value than petroleum-based composites when there are lots of wastage occurred and produced during the process of manufacturing a product [159]. Therefore, it is necessary to minimize the wastages during the manufacturing process. If the biocomposites are managed properly, they will offer good carbon savings [160]. Some of the biocomposites and their percentage of carbon savings are listed in Table 17.

Table 17: Biocomposites with their percentage of carbon savings [160].

Biocomposites (BCs)	Carbon savings (%)
Hemp fiber BC	10–50
Kenaf fiber BC	9.2–10.7
Cellulose fiber BC	16.3–18.7
Cotton fiber BC	40

8. Conclusion

This review paper opens up additive manufacturing as a novel method for developing an acoustic panel with enhanced mechanical and acoustical properties using natural fiber-reinforced composites. Poly(lactic acid) is the trending polymer that can be selected as a polymer matrix which is biodegradable, nontoxic, recyclable, and eco-friendly. Natural fibers as reinforcement can be selected based on the requirements and availability. Composites can be produced by suitable compounding techniques and converted into filaments using suitable spinning techniques. The natural fiber-reinforced filament can be 3D-printed into an acoustic panel using FDM technology. The 3D-printed composites will have minor voids formation between deposition lines. This void formation can be turned as a favor since acoustic panel need small range of pores to absorb sound effectively. The outcome of this approach will be an acoustic panel made of natural fiber-reinforced composites which will be replacing the synthetic fiber based-acoustic panels. This approach will ensure the positivity towards attributes like cost, environmental impact, and sustainability.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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